Top Physics at the Tevatron

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representing the CDF and DØ Collaborations

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Motivations for Studying Top

- Only known fermion with a mass at the natural electroweak scale
  - Special role in precision electroweak physics
  - Window into the problem of EWSB?
- New physics may appear in production (e.g. topcolor) or in decay (e.g. charged Higgs).
- Can only be studied at Tevatron prior to LHC.

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A Brief History of Top

- Observed in 1995 in first ~70 pb^{-1} of Run I data.
- Final Run I top analyses based on ~110 pb^{-1}.
  - Production cross sections in many channels
  - Mass: 174.3 ± 5.1 GeV (CDF/DØ combined)
  - Event kinematics
  - W helicity measurement
  - Limits on single top production, rare/non-SM decays
- Overall consistency with the Standard Model.
- But only ~100 analyzable top events

  → analyses statistics-limited.

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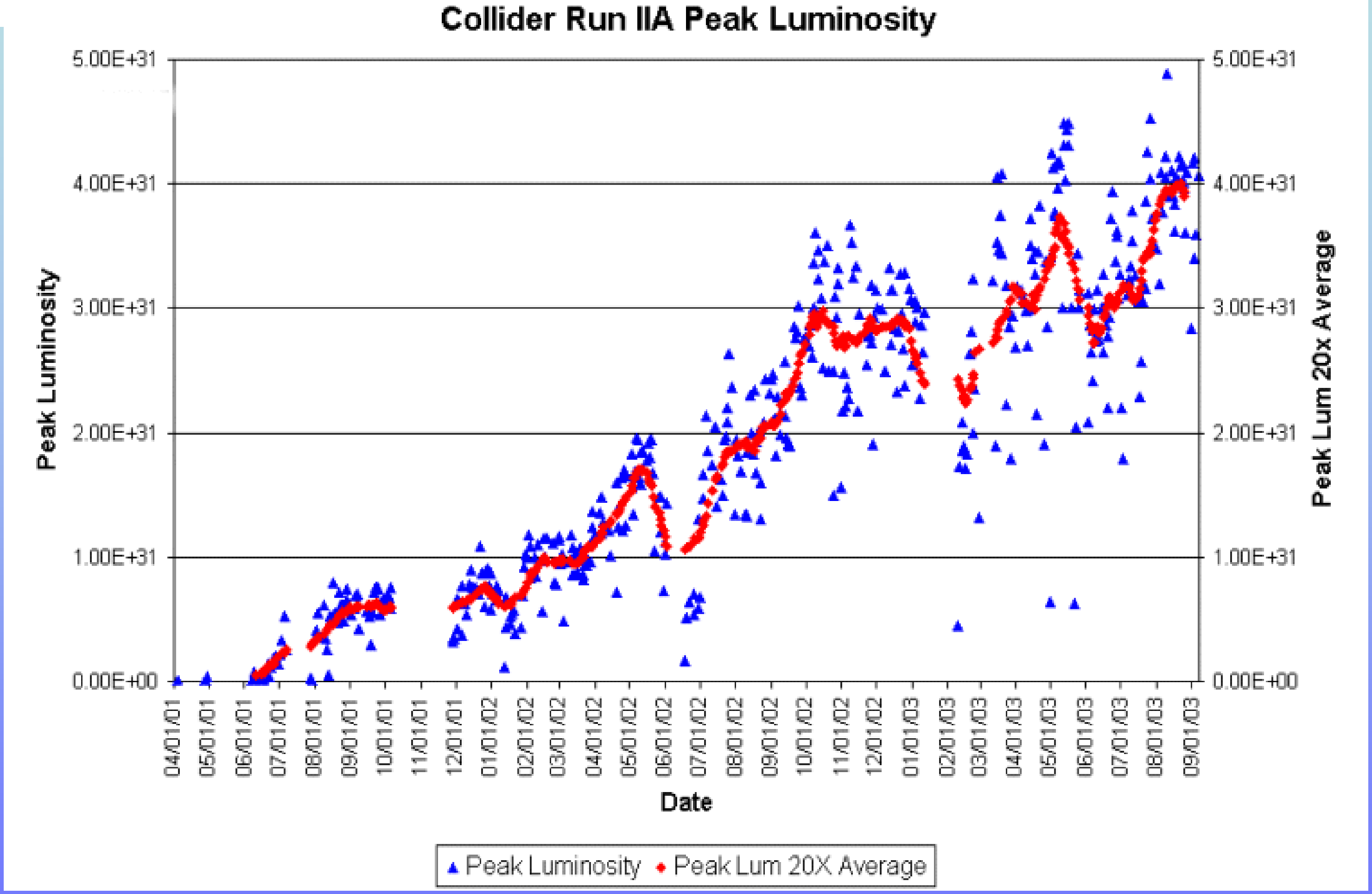
Improvements for Run II

- Accelerator
  - Energy upgrade: 1.8 → 1.96 TeV
    - 30-40% increase in top cross section
  - Luminosity upgrades: factor of ~2-3 so far
- Detectors
  - CDF: new Si vertex detector, outer tracker, endplug calorimeter, extended muon coverage
  - DØ: magnetic tracking system (scint. fibers + silicon), preshower system, muon upgrades
  - Both: Upgraded DAQ/trigger systems to deal with change from 3.5μs to 396 ns bunch crossing interval.

Tevatron Peak Luminosity



Typical recent stores: $3\text{-}4 \times 10^{31}$

Run IIa goal: 8×10^{31}

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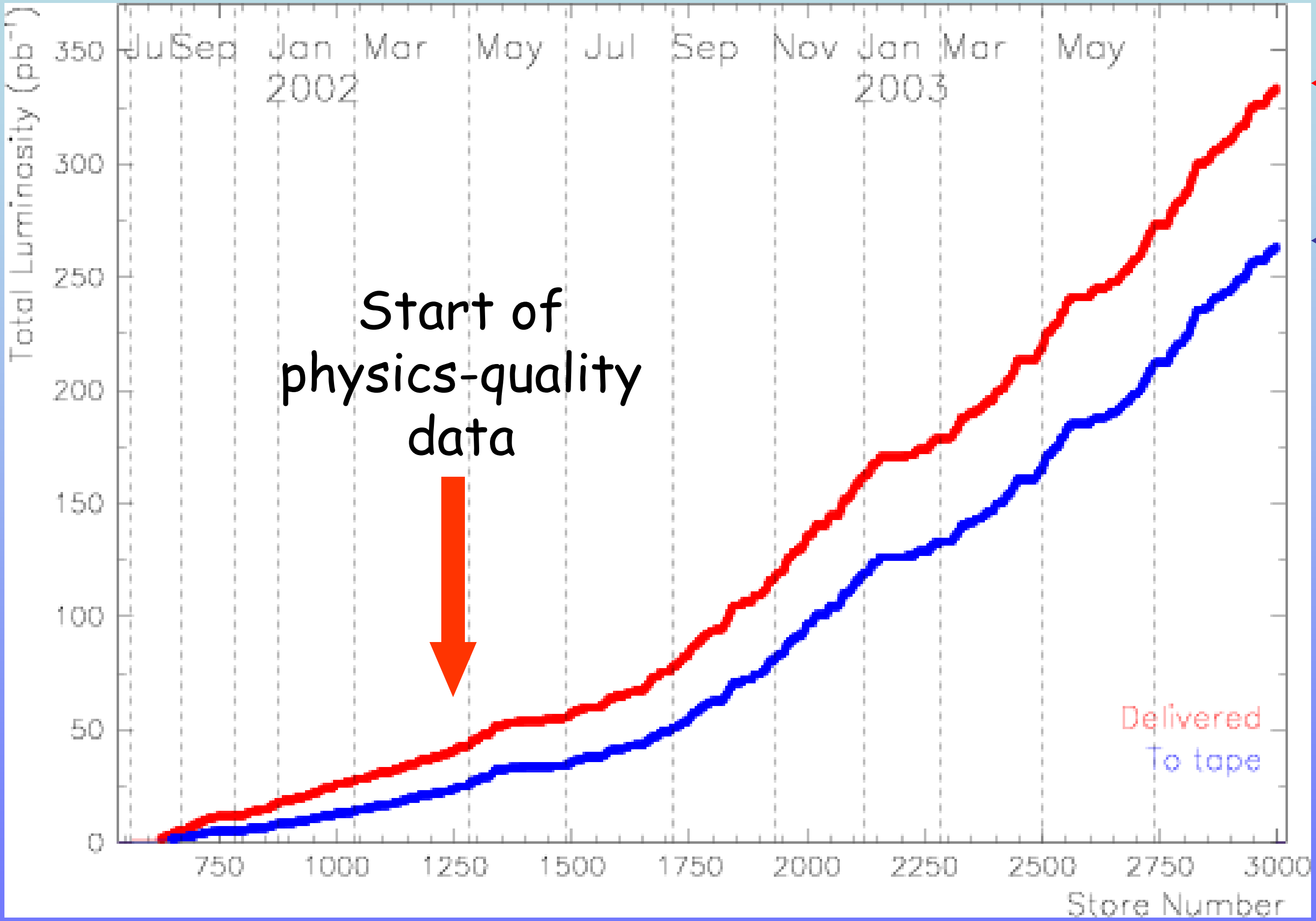
Integrated Luminosity



delivered ~325 pb^{-1}

on tape ~270 pb^{-1}

Taking data with ~90% efficiency

Results from first ~100 pb^{-1} presented today.

Goal for 2004: additional 310-380 pb^{-1} delivered.

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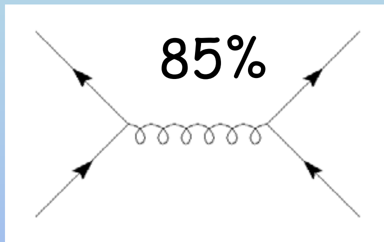
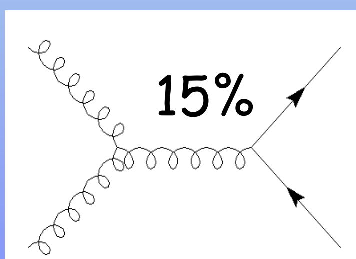
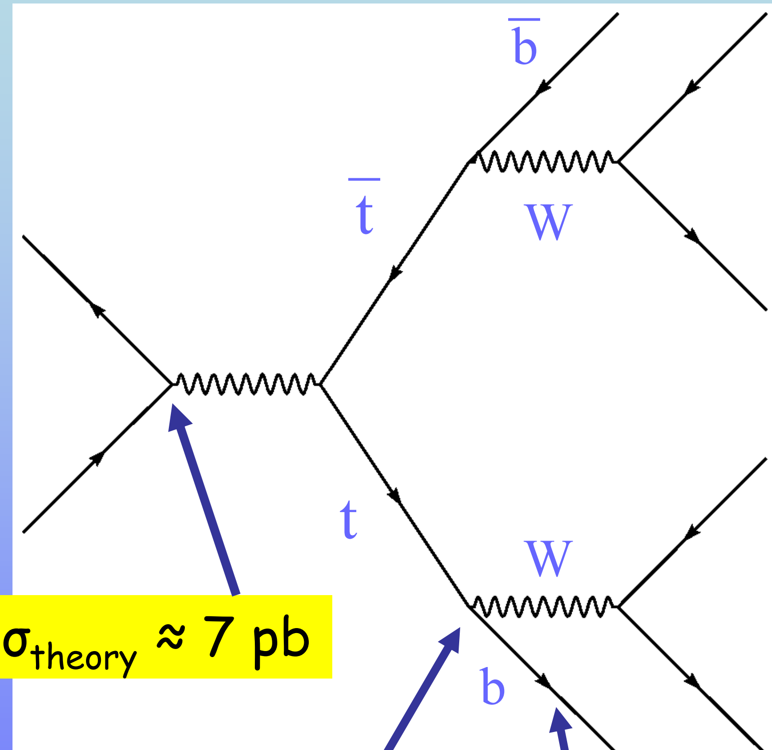
Production and Decay Basics

Pair Production:





NB: qq, gg fractions reversed at LHC



$\sigma_{theory} \approx 7$ pb

$\mathrm{BR}(\, t \rightarrow Wb) \approx 100\%$

b-jet: identify via secondary vertex or soft lepton tag

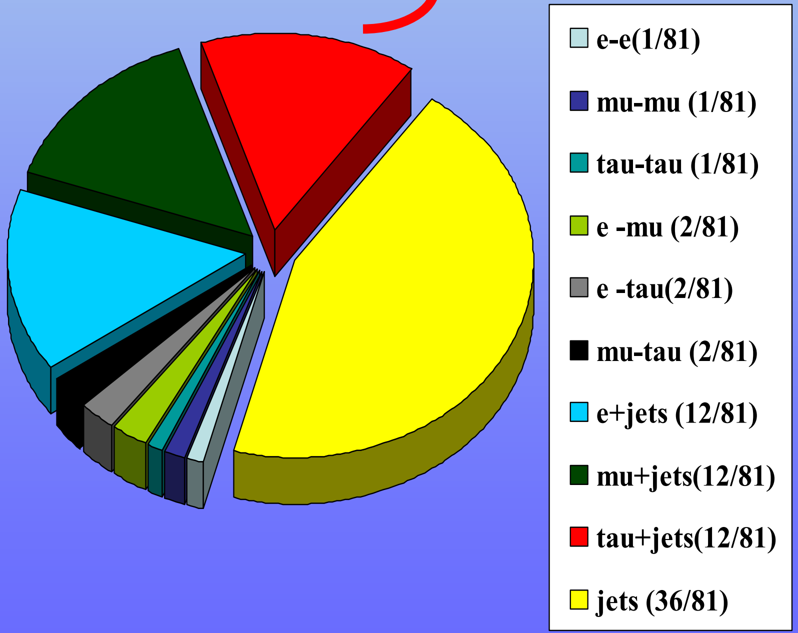
Event topology determined by the decay modes of the W's

t-tbar Final States

- Dilepton (ee, μμ, eμ)
  - BR = 5%
  - 2 high-P_T leptons + 2 b-jets + missing-E_T
- Lepton (e or μ) + jets
  - BR = 30%
  - single lepton + 4 jets (2 from b's) + missing-E_T
- All-hadronic
  - BR = 44%
  - six jets, no missing-E_T
- τ_{had} +X
  - BR = 23%

Most favorable channels for top physics

More challenging backgrounds, but measurements still possible



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Measuring the ttbar Cross Section

- Basic engineering number, starting point for all top physics.
- Requires detailed understanding of backgrounds and selection efficiencies.
- Test of QCD
  - Latest calculations: NNLO + NNNLL
  - Departures from prediction could indicate nonstandard production mechanisms, i.e. production through decays of SUSY states.

Dilepton Cross Sections: DØ

Results from first 90 – 110 pb^{-1}

- ee channel
  - Observe 2 events, bkgd. 0.6 ± 0.5
- μμ channel
  - Observe 0 events, bkgd. 0.7 ± 0.4
- eμ channel
  - Observe 3 events, bkgd. 0.4 ± 0.4)

$$\sigma_{t\bar{t}} = 8.7 \,^{+6.4}_{-4.7}(\text{stat}) \,^{+2.7}_{-2.0}(\text{syst}) \pm 0.9(\text{lum})\,\text{pb}$$

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Dilepton Cross Section: CDF

Two complementary analyses (126 pb^{-1})

- Tight: Two good-quality leptons + MET + 2 jets
  - **10 candidates** (2 ee, 3 μμ, 5 eμ), bkgd. **2.9 ± 0.9**
  - **6 events b-tagged (one double-tag); expect 4 top**
  - $\boxed{\sigma_{tt} = \mathbf{7.6 \pm 3.4\ (stat) \pm 1.5\ (sys)\ pb}}$
- Loose: Lepton + isolated track + MET + 2 jets
  - **13 candidates**, bkgd. **5.1 ± 0.9**
  - **5 events b-tagged (one double-tag); expect 4 top**
  - $\boxed{\sigma_{tt} = \mathbf{7.3 \pm 3.4\ (stat) \pm 1.7\ (sys)\ pb}}$

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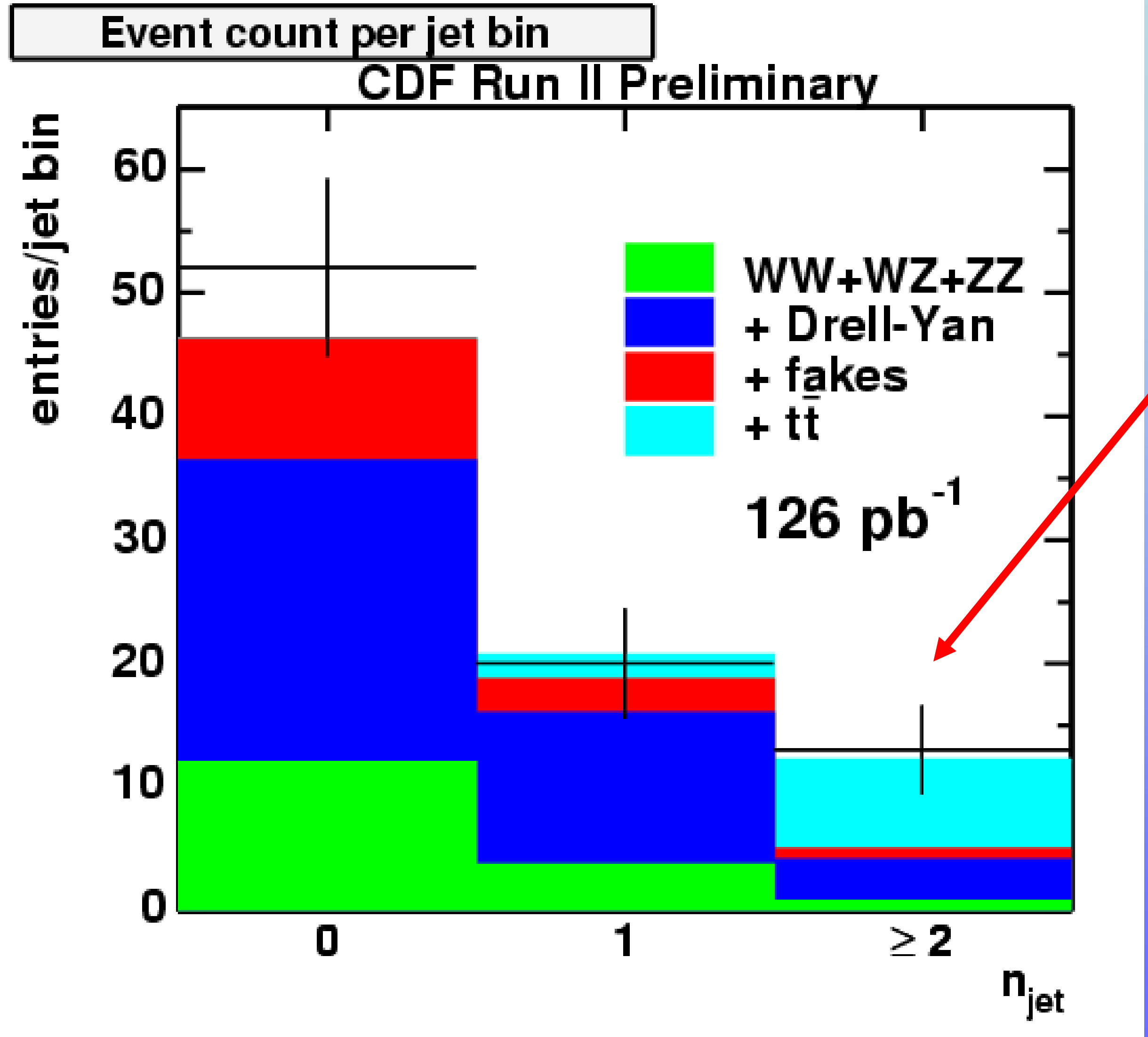
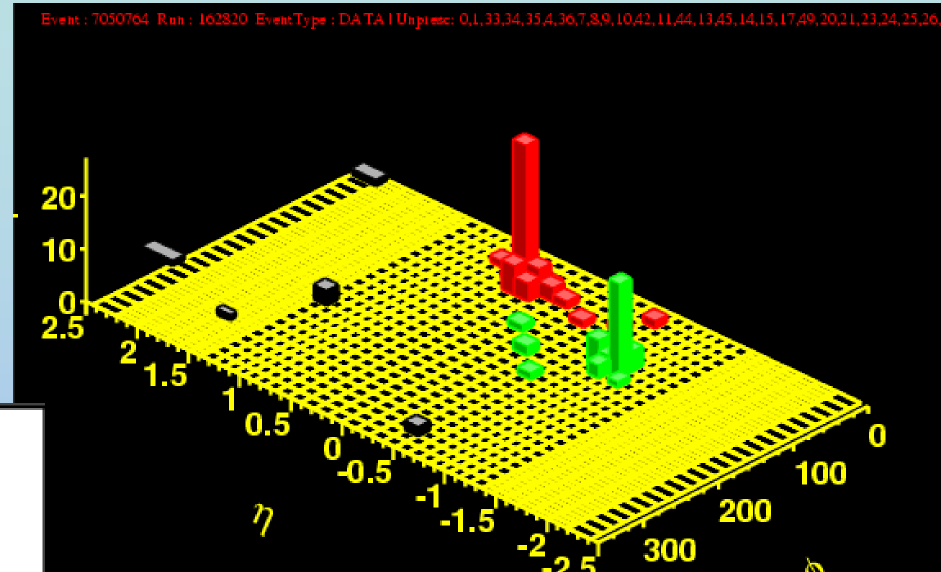
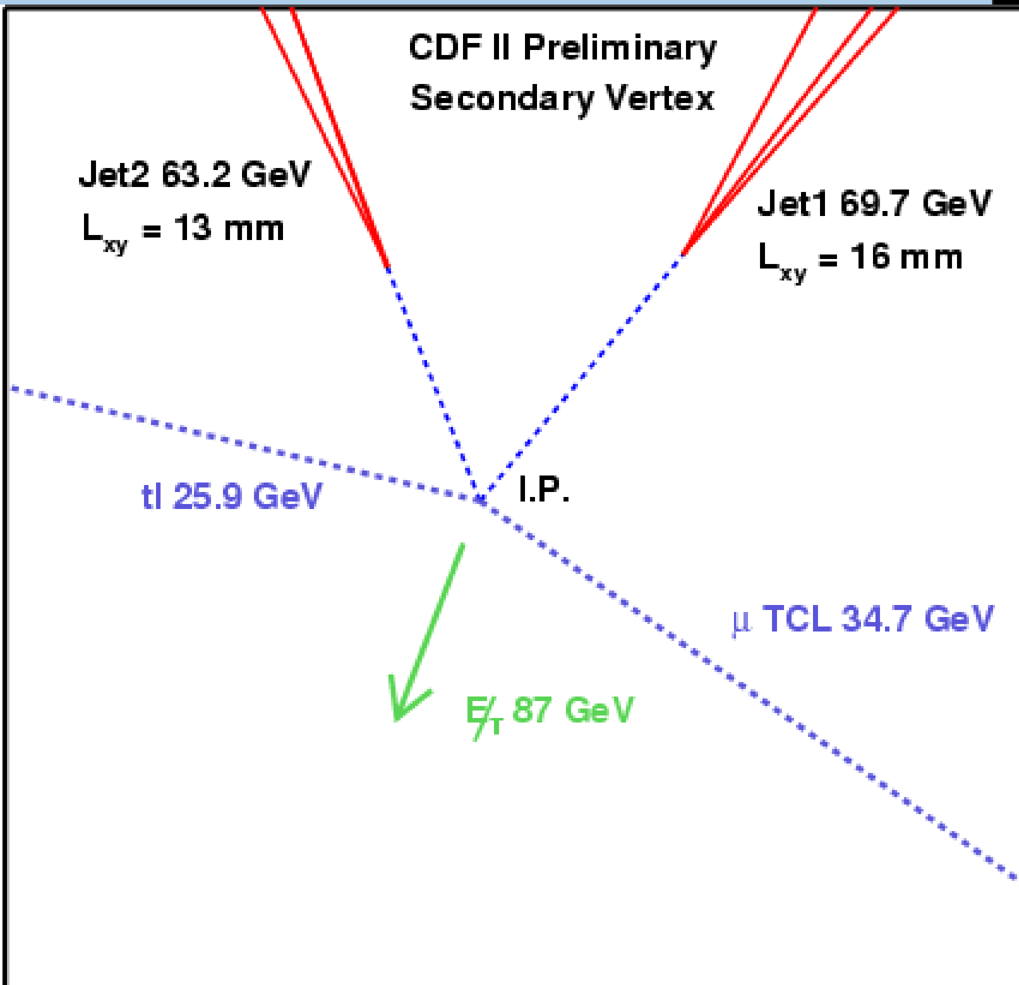
Jet Multiplicity in Dilepton Events

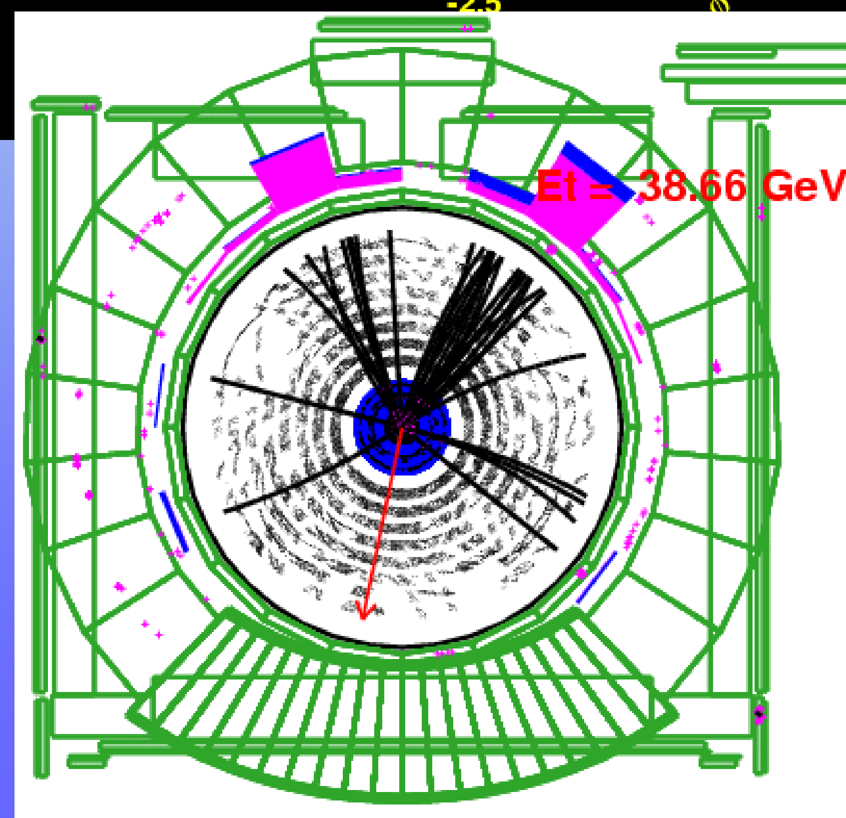


ttbar signal bin

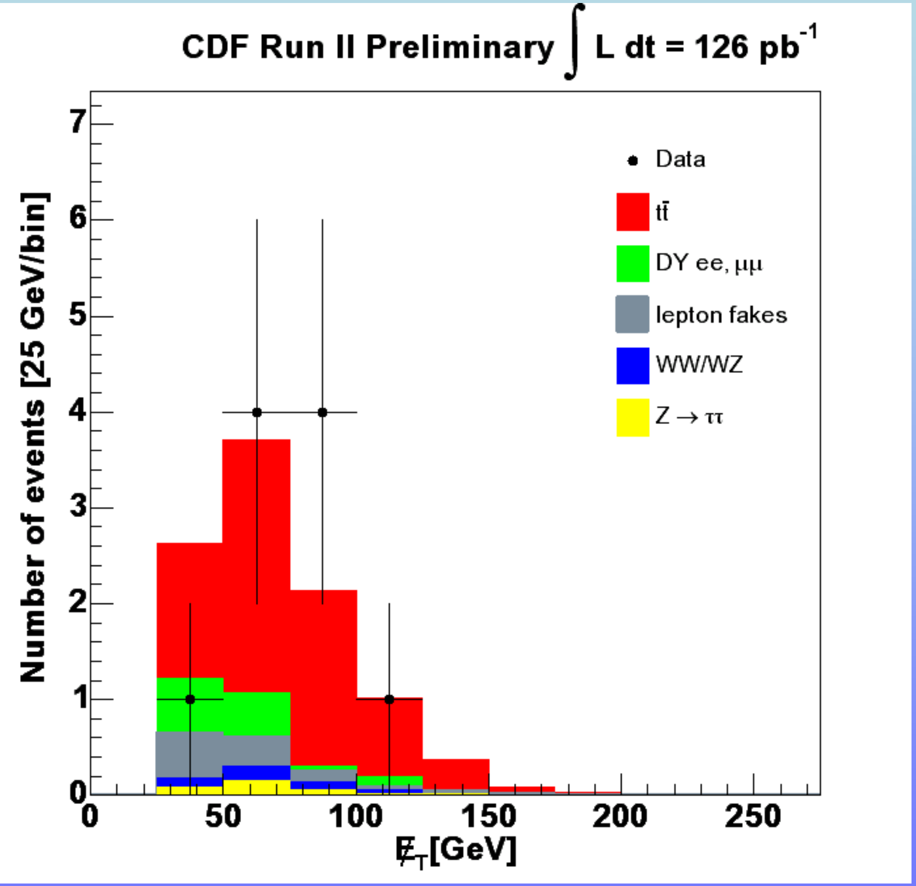
Double b-tagged Lep+Trk event at CDF

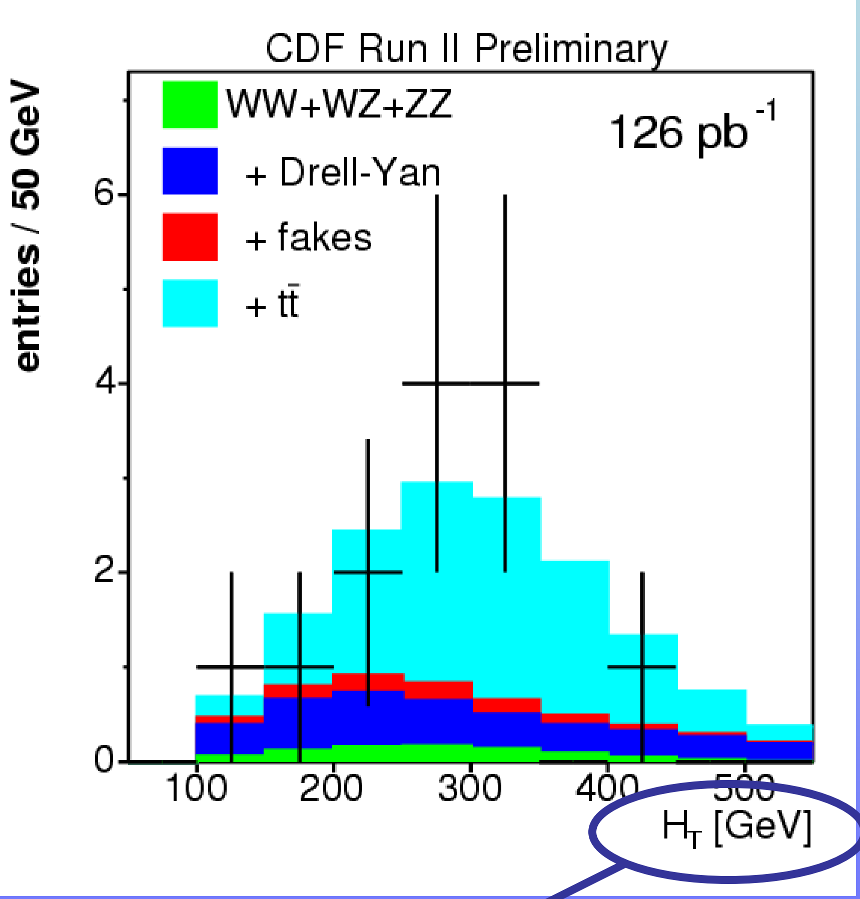






Dilepton Kinematics

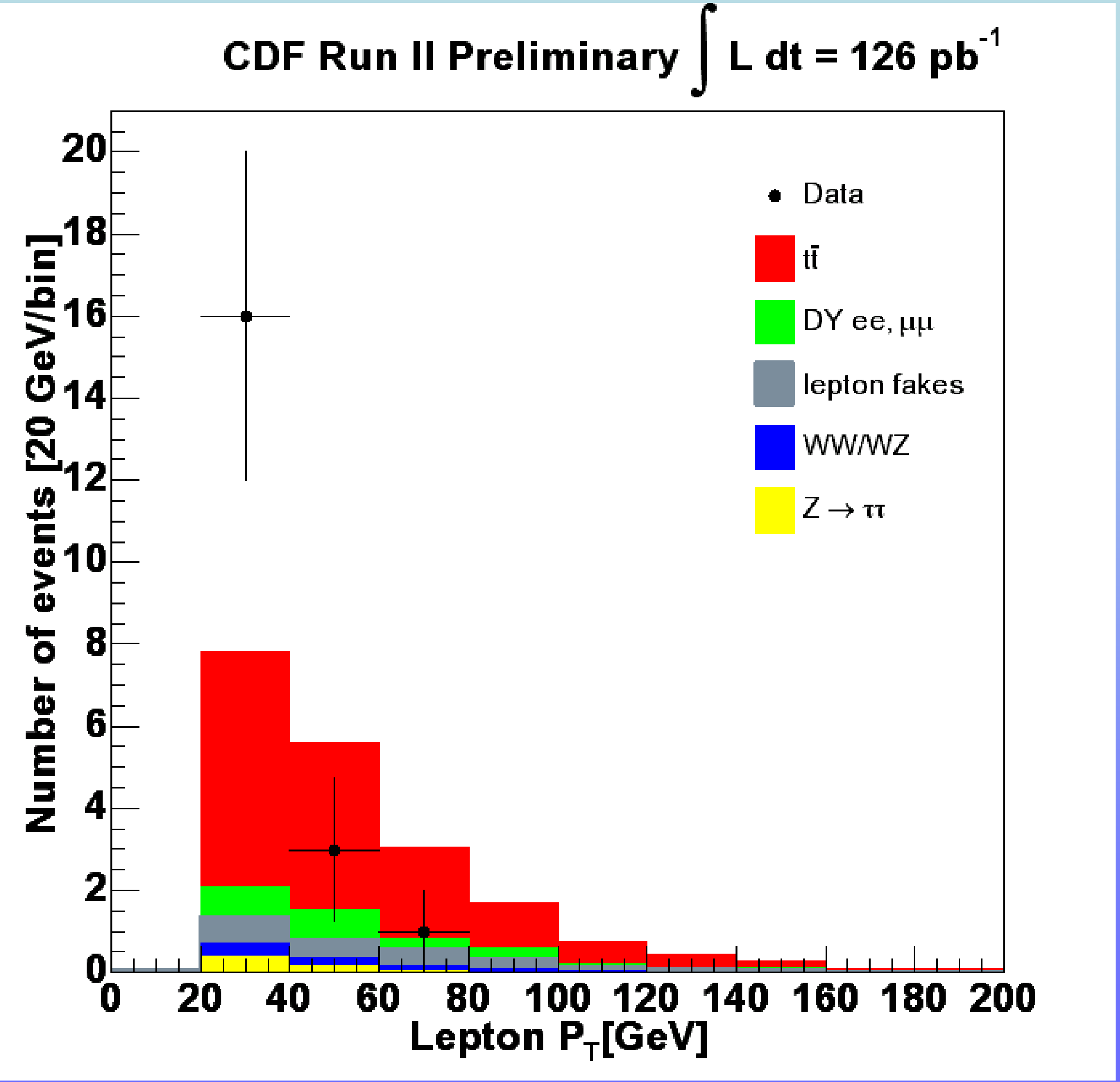




Scalar summed E_T of jets, leptons, and missing E_T

Dilepton Kinematics, contd.

Lepton P_T softer than expected. Statistical fluctuation or a hint of something new?



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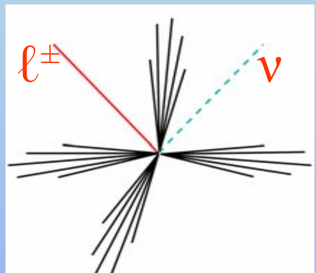
Lepton + Jets Cross Section: DØ

Using topological cuts

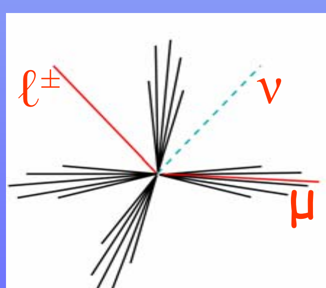


Backgrounds from QCD estimated from data as fcn. of MET, Njets.

Backgrounds from W+jets estimated using Berends scaling hypothesis, $\sigma(W+n+1 \text{ jets})/\sigma(W+n \text{ jets}) = \text{constant}$.

After aplanarity, H_T , Njet $\geq$ 4 cuts: observe 26 events, bkgd. 18.5 ± 2.5.

Using soft muon b-tag



Orthogonal selection to topological analysis.

QCD and W+jets backgrounds estimated as in topological analysis.

Fake tag rate estimated using jet data.

Observe 15 events, bkgd. 3.3 ± 1.3.

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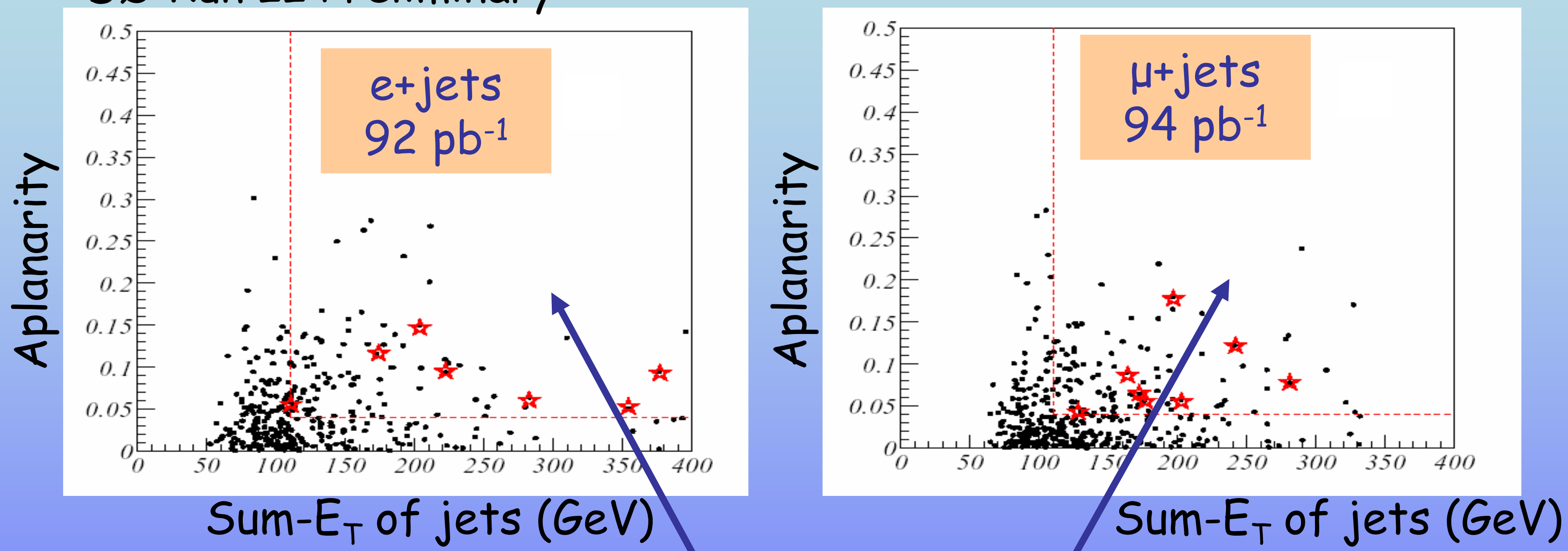
Lepton + Jets Kinematics

DØ Run II Preliminary



b-tagged events populate the top signal region

$$\sigma_{t\bar{t}} = 8.0\ ^{+2.4}_{-2.1}\,(\mathrm{stat})\ ^{+1.7}_{-1.5}\,(\mathrm{syst}) \pm 0.8\,(\mathrm{lum})\ \mathrm{pb}$$

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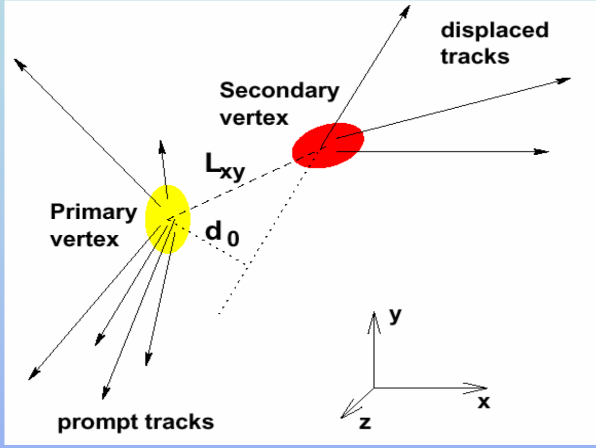
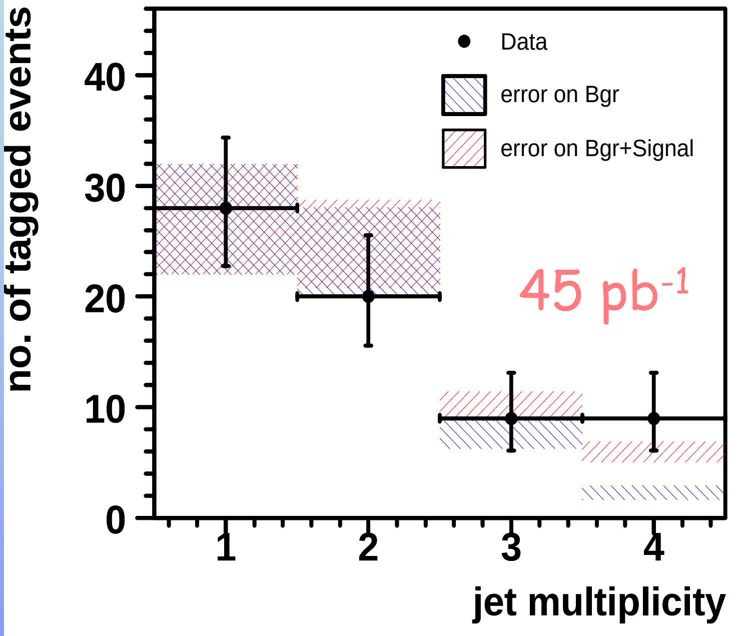
Lepton + jets with Secondary Vertex B-Tag at DØ





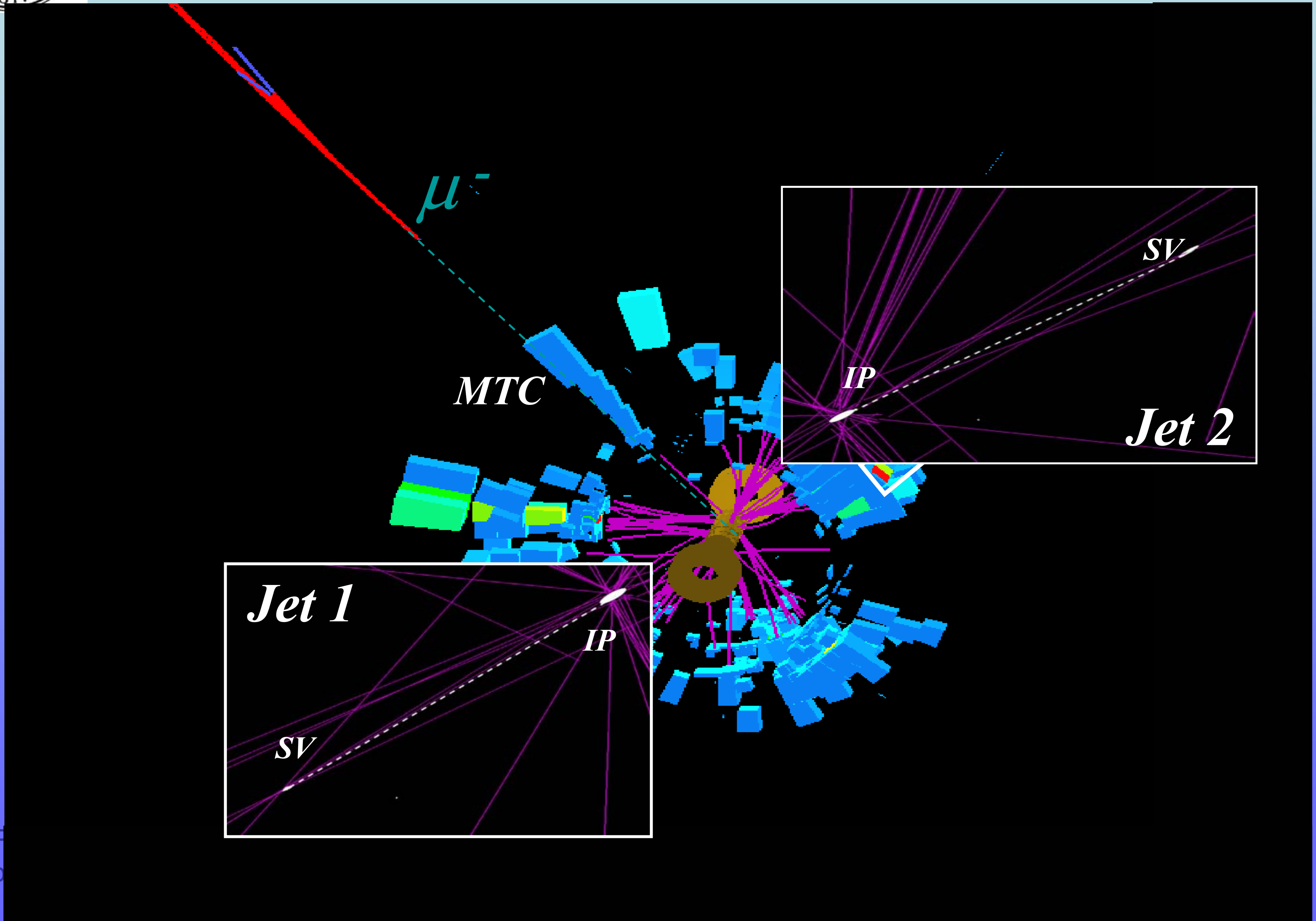
Tag by reconstructing sec. vtx.:

$$\sigma_{t\bar{t}} = 10.8^{+4.9}_{-4.0}(stat)^{+2.1}_{-2.0}(syst) \pm 1.1(lum)\ pb$$

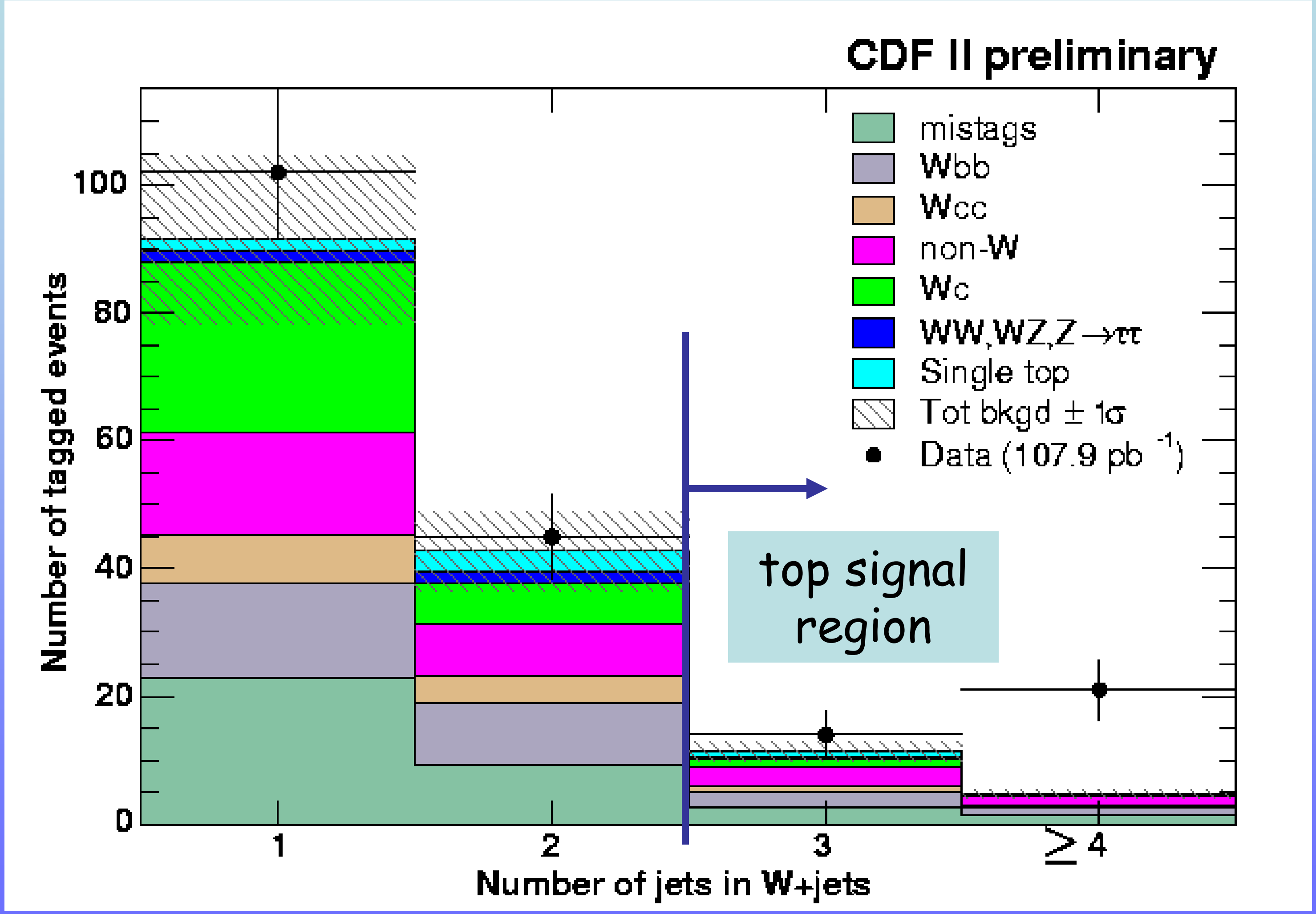
Tag by counting displaced tracks:

$$\sigma_{t\bar{t}} = 7.4^{+4.4}_{-3.6}(stat)^{+2.1}_{-1.8}(syst) \pm 0.7(lum)\ pb$$

μ+jets double tagged event at DØ



Jet Multiplicity in b-tagged events: CDF



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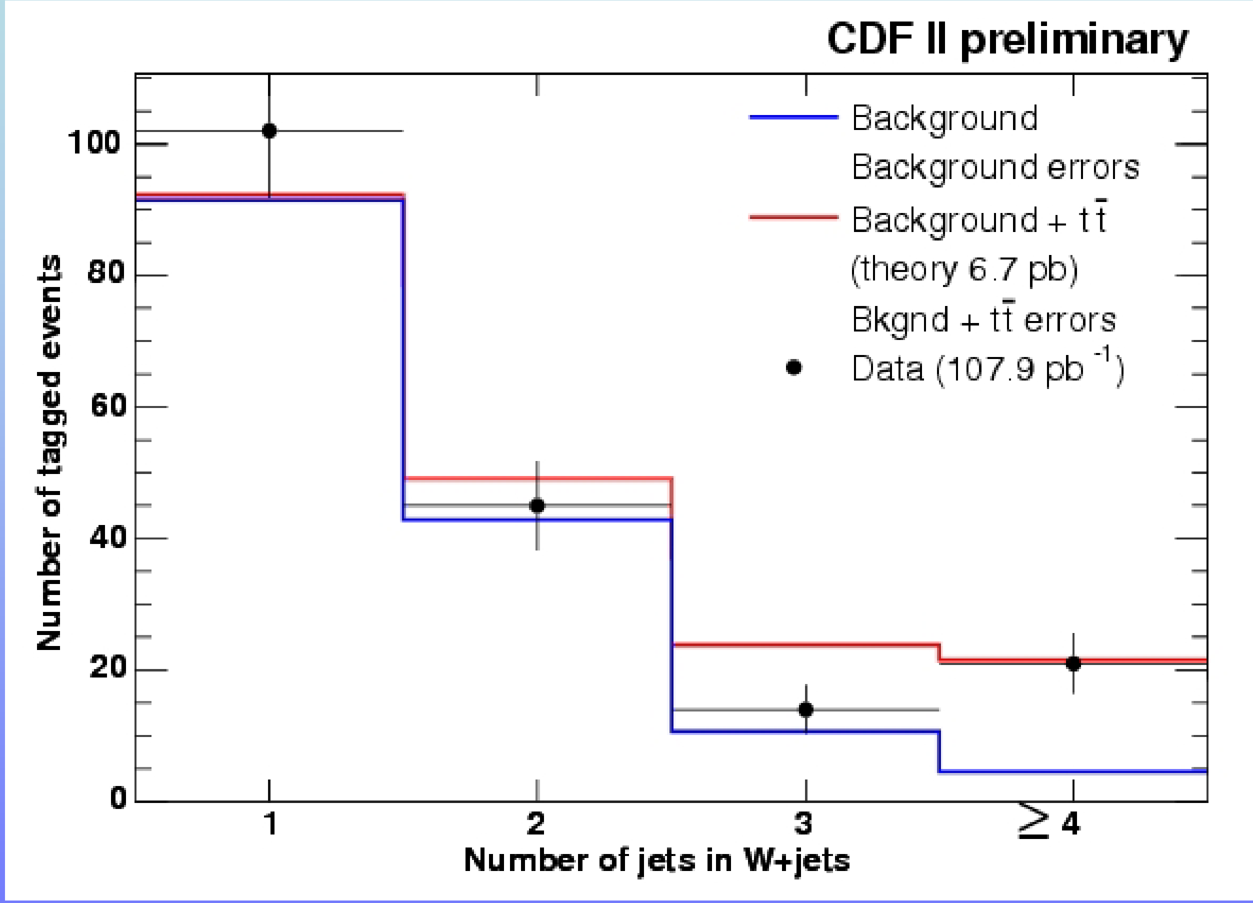
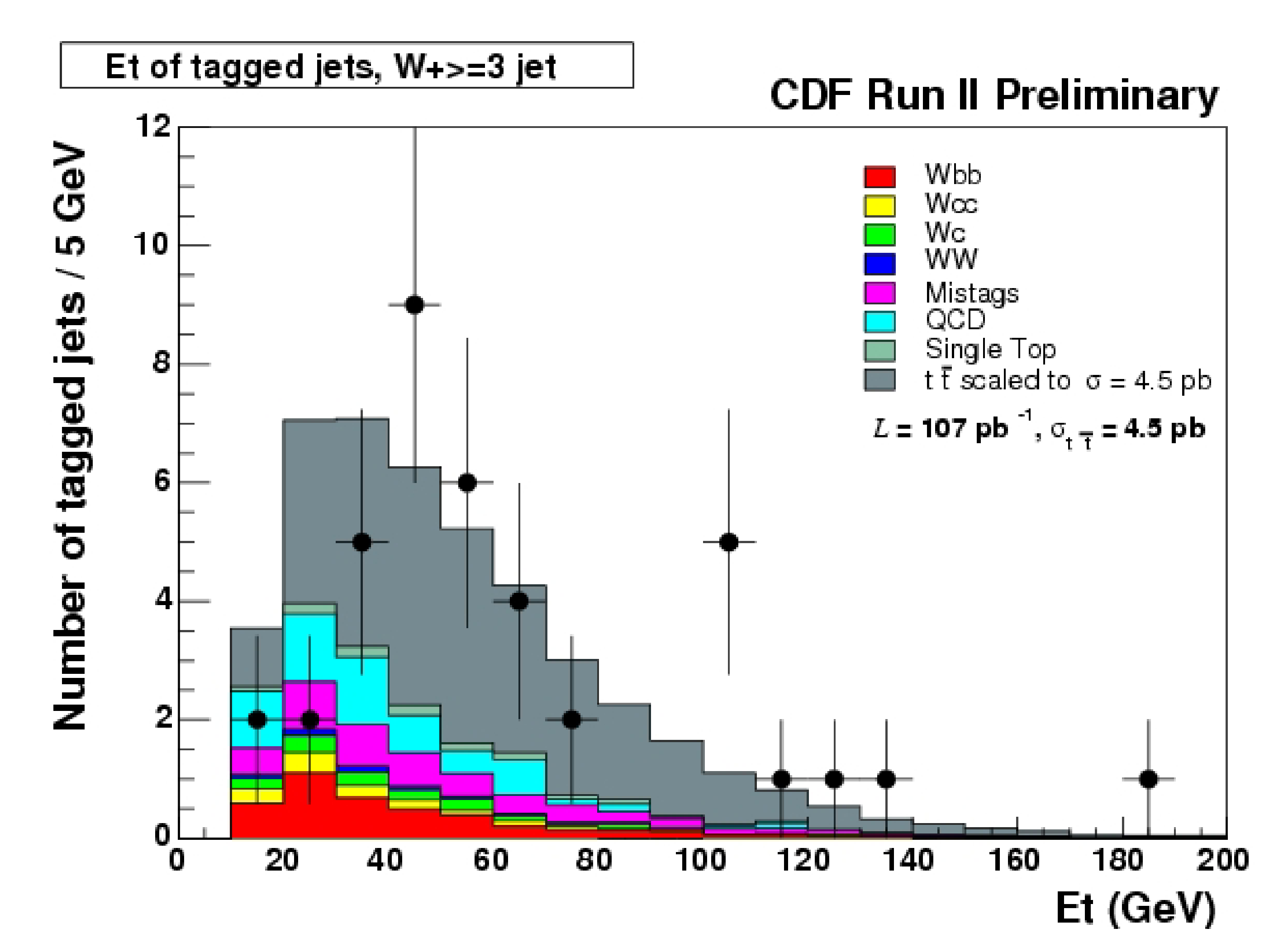
Jet Multiplicity (with top contribution)



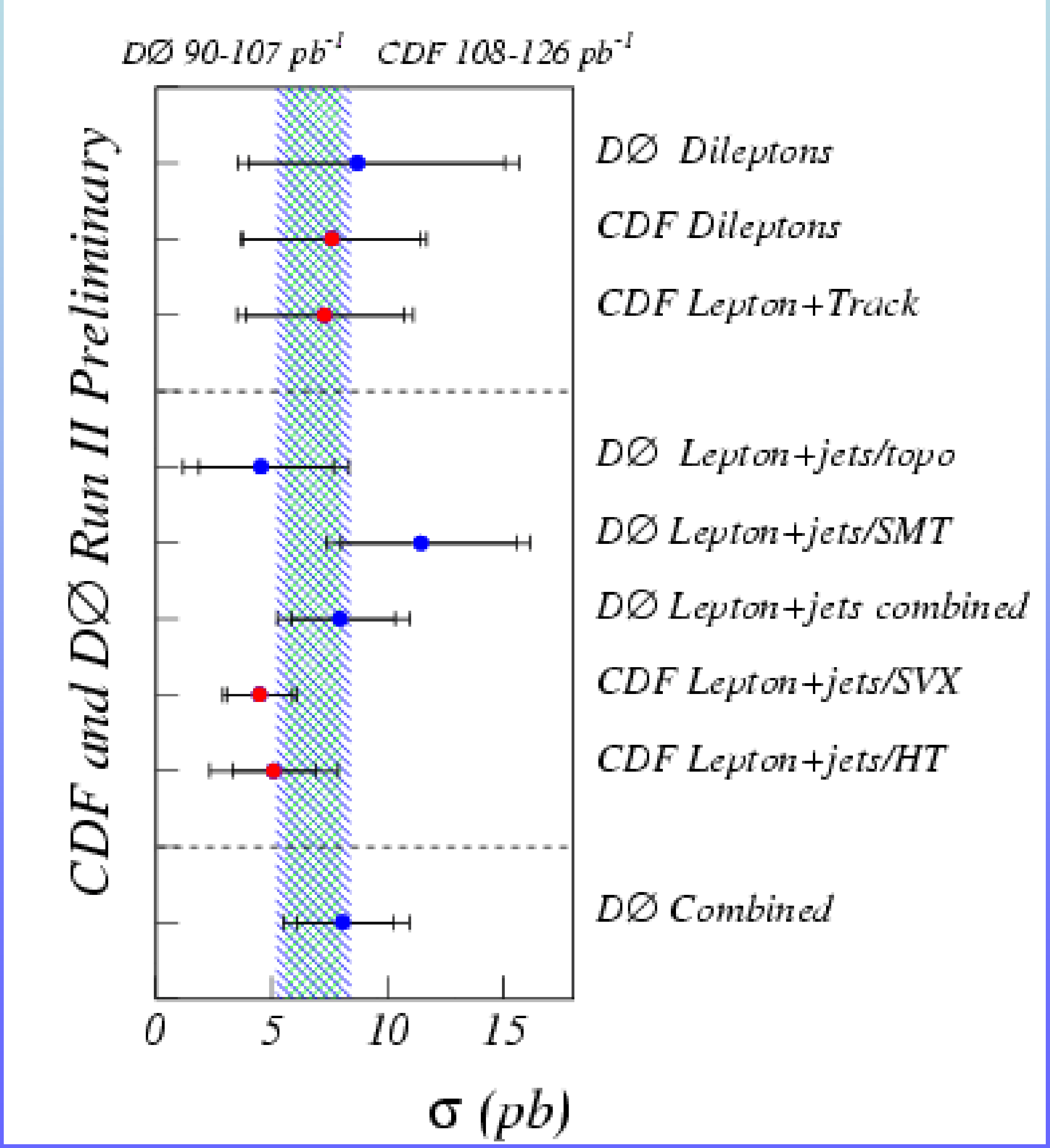
$$\sigma_{l+jets} = 4.5 \pm 1.4(\text{stat}) \pm 0.8(\text{syst})\ \text{pb}$$

New for ICFP2003

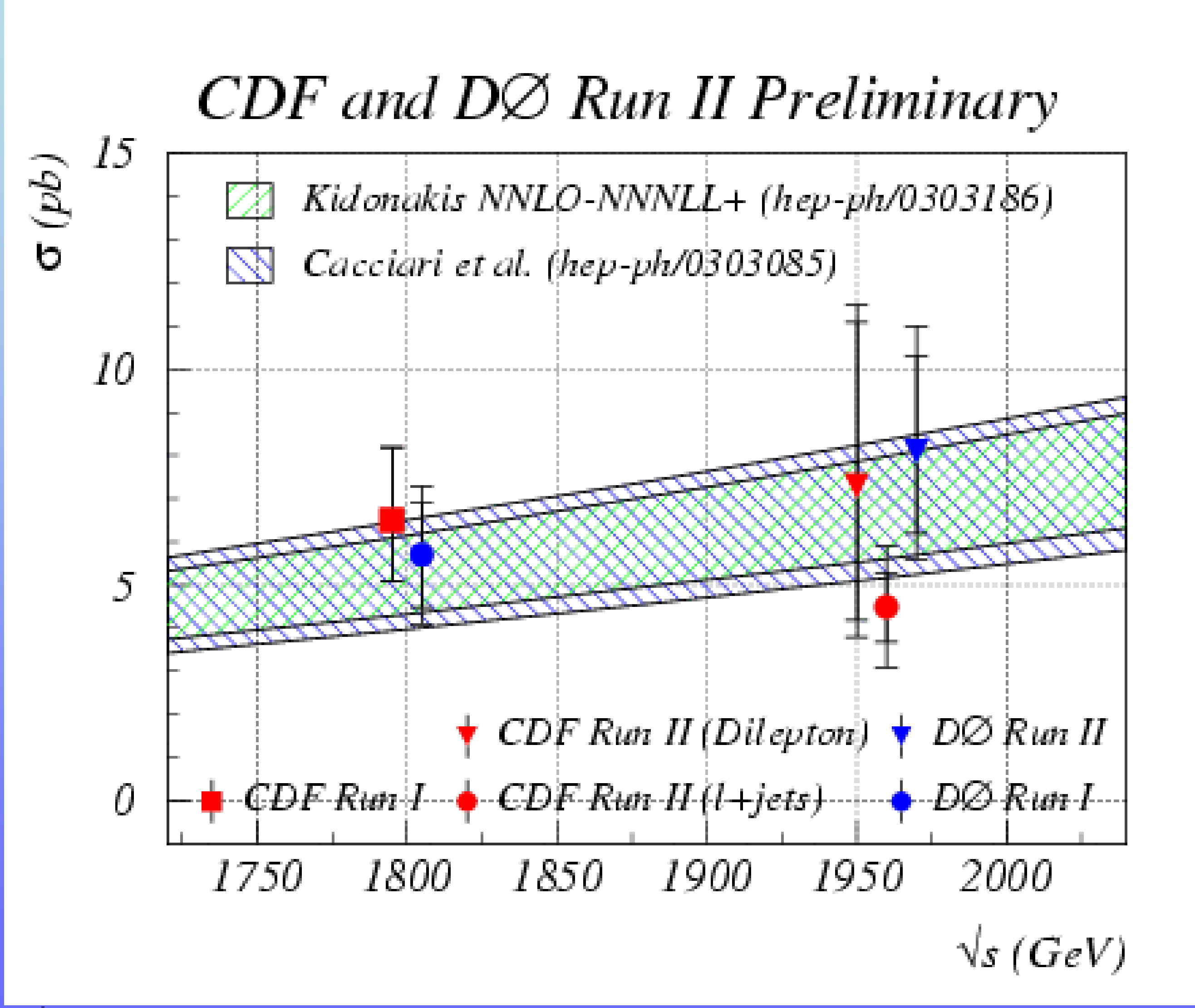
L+jets: Tagged Jet E_T



Summary of Cross Section Results

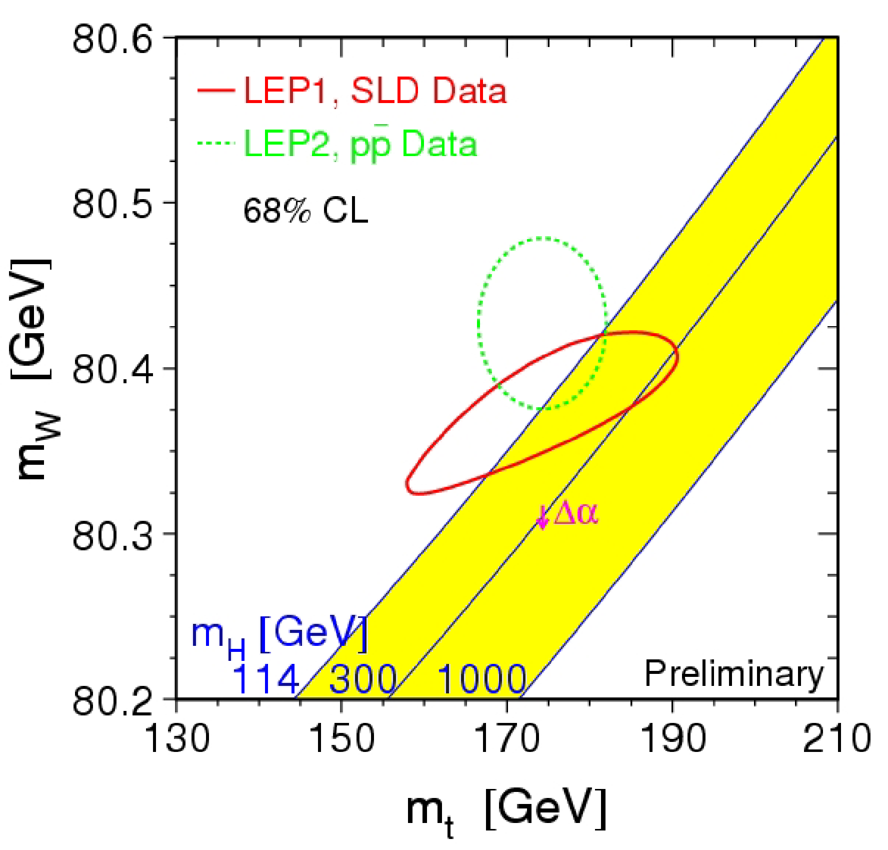


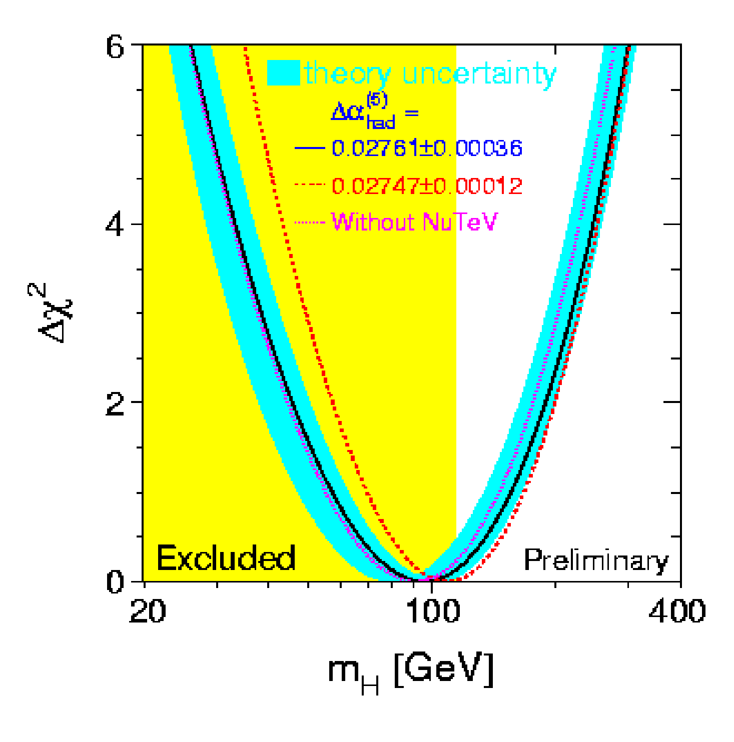
Cross Section √s-Dependence



Top Mass Measurement

M_{top} is a precision electroweak parameter that helps constrain the mass of the Higgs.





Top Mass in Run II (CDF)

- Lepton + 4 jets with sec. vertex b-tag
  - Many kinematic constraints: 4C fit
  - 12 parton/jet matching assignments possible; pick combination with lowest χ^2.
  - Fit resulting to mass distribution to background + signal templates.
- Dilepton channel
  - Underconstrained system
  - Use $P_{ttbar,z}$ to weight the mass fit distribution
  - Likelihood fit to top mass templates.

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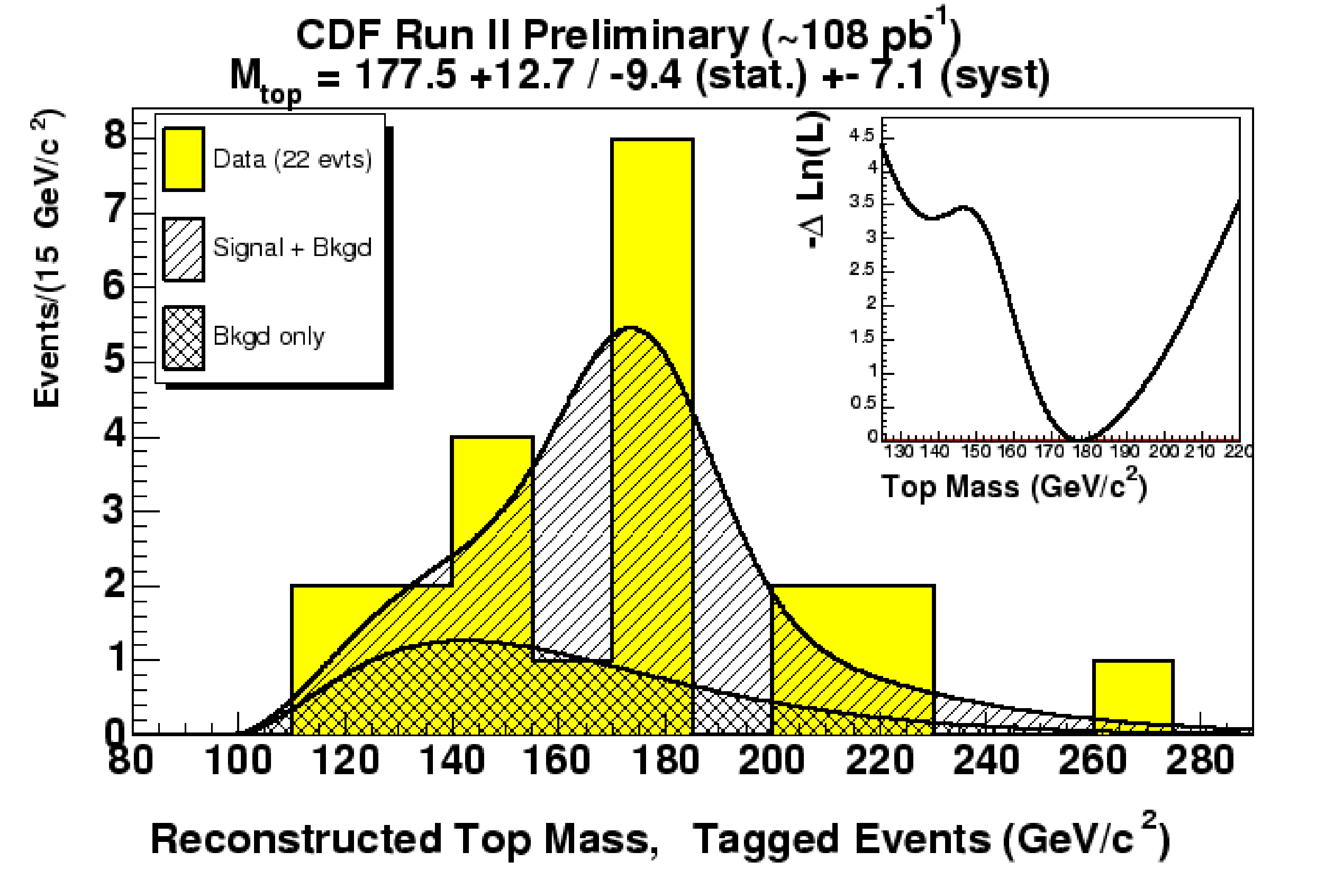
Run II Top Mass: lepton + jets



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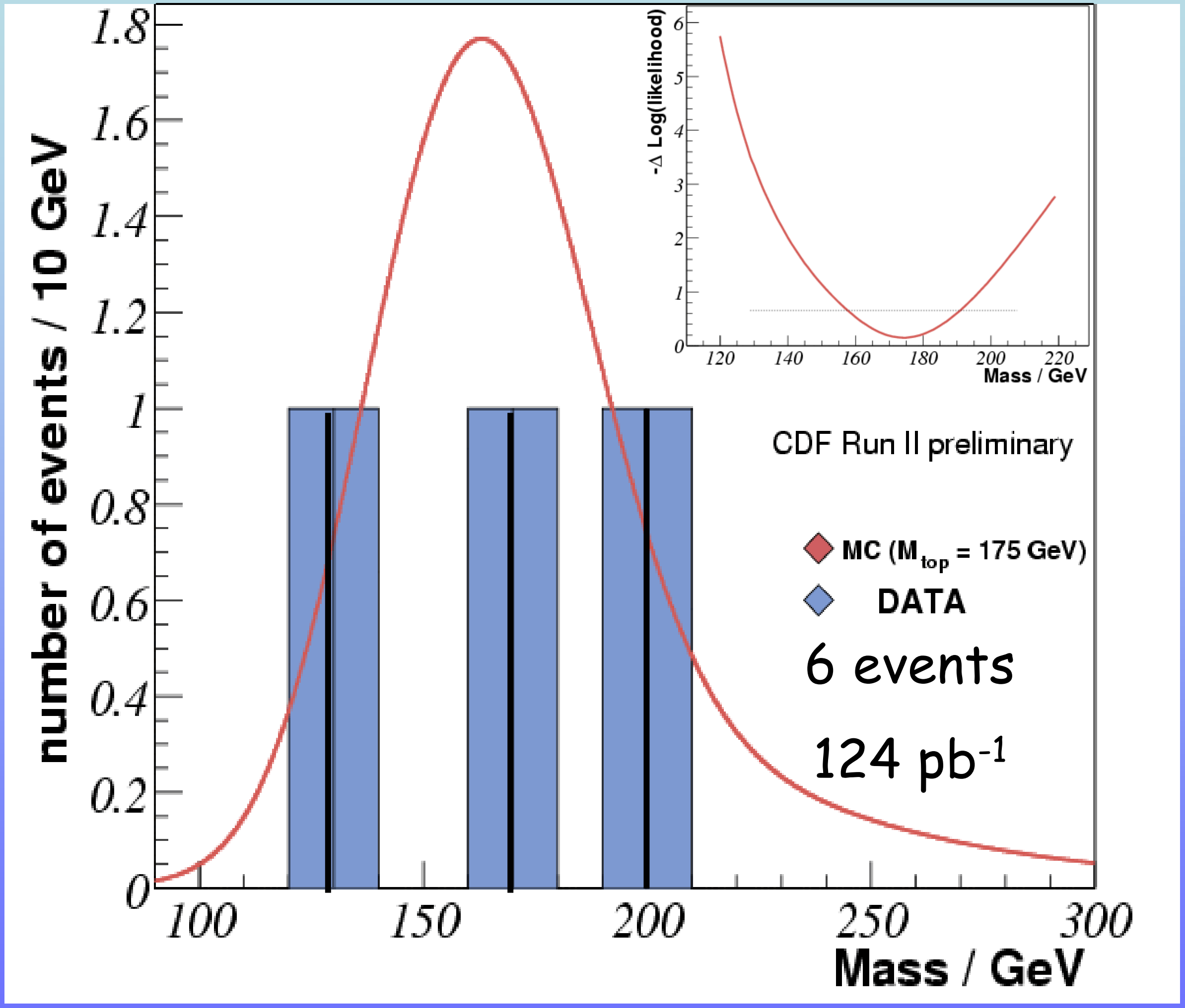
Run II Top Mass: Dilepton Channel



$$175.0^{+17.4}_{-16.9}\,(\text{stat}) \pm 7.9\,(\text{syst})\ \text{GeV}/c^2$$

New Run I Mass Measurement (DØ)

- The template method has some disadvantages:
  - One combination chosen for fit
  - Single template describes the distribution
  - All events treated with equal weight
- New analysis makes better use of available information
  - All measured quantities used in fit (except unclustered energy)
  - Each event has its own probability distribution
  - Well-measured events contribute more

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Matrix Element Method

$d^n\sigma$ is the differential cross section

W(y,x) is the probability that a parton level set of variables ***y*** will be measured as a set of variables ***x***

$$P(x;\alpha) = \frac{1}{\sigma}\int d^n\sigma(y;\alpha)\,\underline{dq_1\,dq_2\;f(q_1)\,f(q_2)}\,W(x,y)$$

f(q) is the probability distribution than a parton will have a momentum ***q***

$$P(x;\alpha) = c_1 P_{ttbar}(x;\alpha) + c_2 P_{background}(x)$$

- Leading-Order ttbar->lepton+jets matrix element, PDFs
- 12 jet permutations, all values of P(ν)
- Phase space of 6-object final state
- Detector resolutions

- Only *W*+jets, 80%
- VECBOS subroutines for *W*+jets
- Same detector resolutions as for signal
- All permutations, all values of P(ν)
- Integration done over the jet energies

- Convolute probability to include all conditions for accepting or rejecting an event

$$P_{measured}(x;\alpha) = Acc(x)P(x;\alpha)$$

- Form a Likelihood as a function of: Top Mass, F_0 (longitudinal fraction of W bosons)

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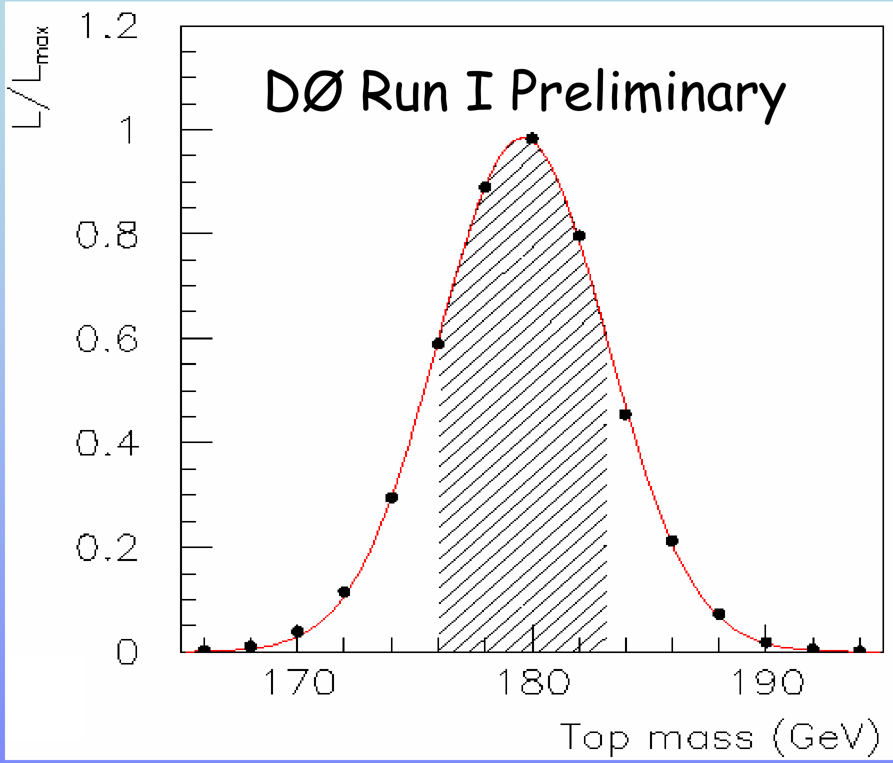
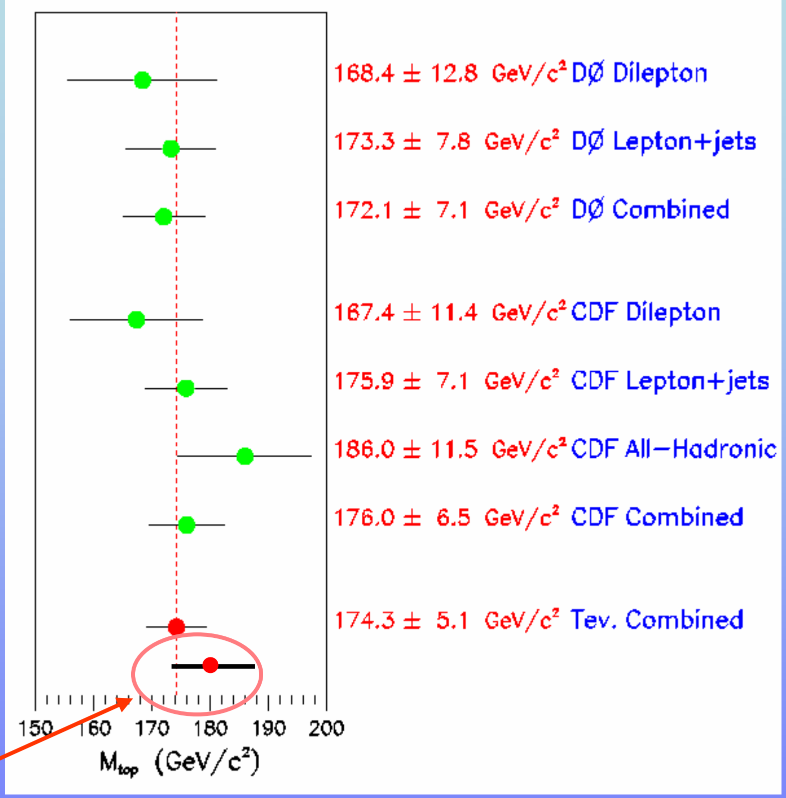
Error Comparable to Previous Run I Measurements Combined





$$M_{top} = 180.1 \pm 3.6\ (\text{stat}) \pm 4.0\ (\text{syst})\ \text{GeV}/c^2$$

Previous DØ result using template method had stat. uncertainty of 5.6 GeV. New method is equivalent to 2.4 times more data!

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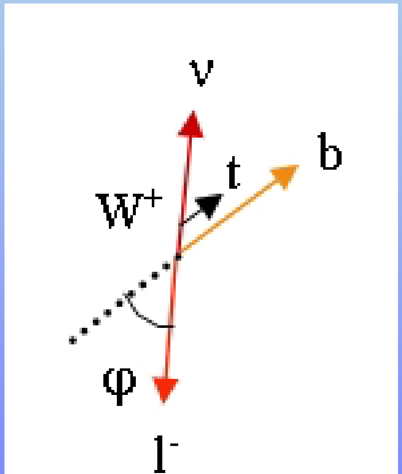
W Helicity Measurement

- Top decays before it can hadronize, because width Γ_t = 1.4 GeV > Λ_{QCD}.
  - Decay products preserve information about the underlying Lagrangian.
  - Unique opportunity to study the weak interactions of a bare quark, with a mass at the natural electroweak scale!
- SM Prediction:
  - W helicity in top decays is fixed by M_{top}, M_W, and V-A structure of the tWb vertex.

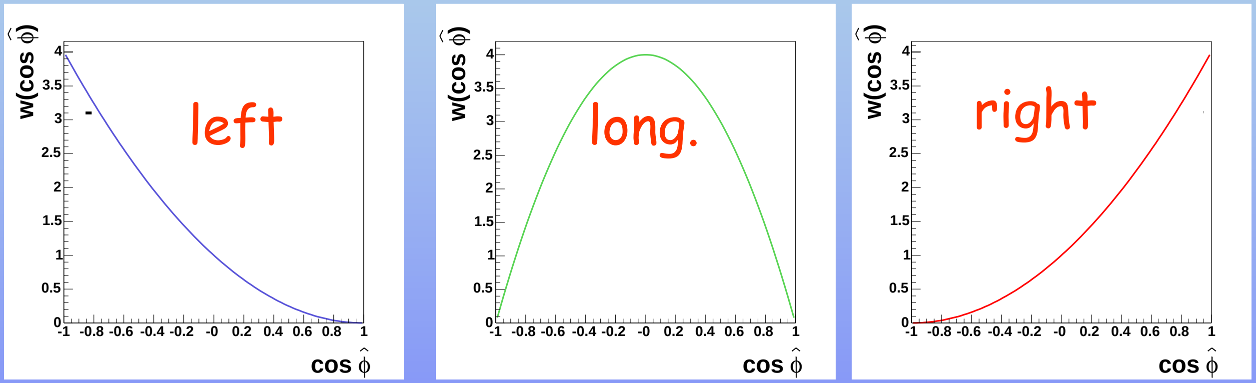
W Helicity Measurement, contd.

The angular dependence of the semileptonic decay in the W rest frame is given by

$$w(\cos\varphi_{l^-\bar{b}}) = F_- \cdot \frac{3}{8}(1-\cos\varphi_{l^-b})^2 + F_0 \cdot \frac{3}{8}(1-\cos^2\varphi_{l^-b}) + F_+ \cdot \frac{3}{8}(1+\cos\varphi_{l^-b})^2$$



W rest frame



SM predictions (for m_b=0):

$$F_- = \frac{2\omega}{1+2\omega} \approx 0.3 \qquad F_0 = \frac{1}{1+2\omega} \approx 0.7 \qquad F_+ = 0$$

where $\omega = M_W^2/M_{top}^2$

parameter to measure

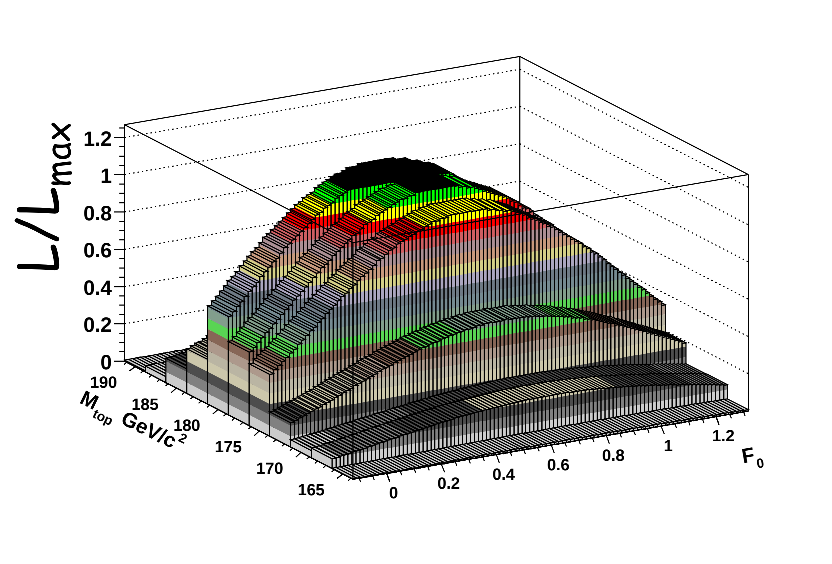
W Helicity Results

New DØ Run I measurement:

• Natural extention of the ME method developed for top mass measurement.

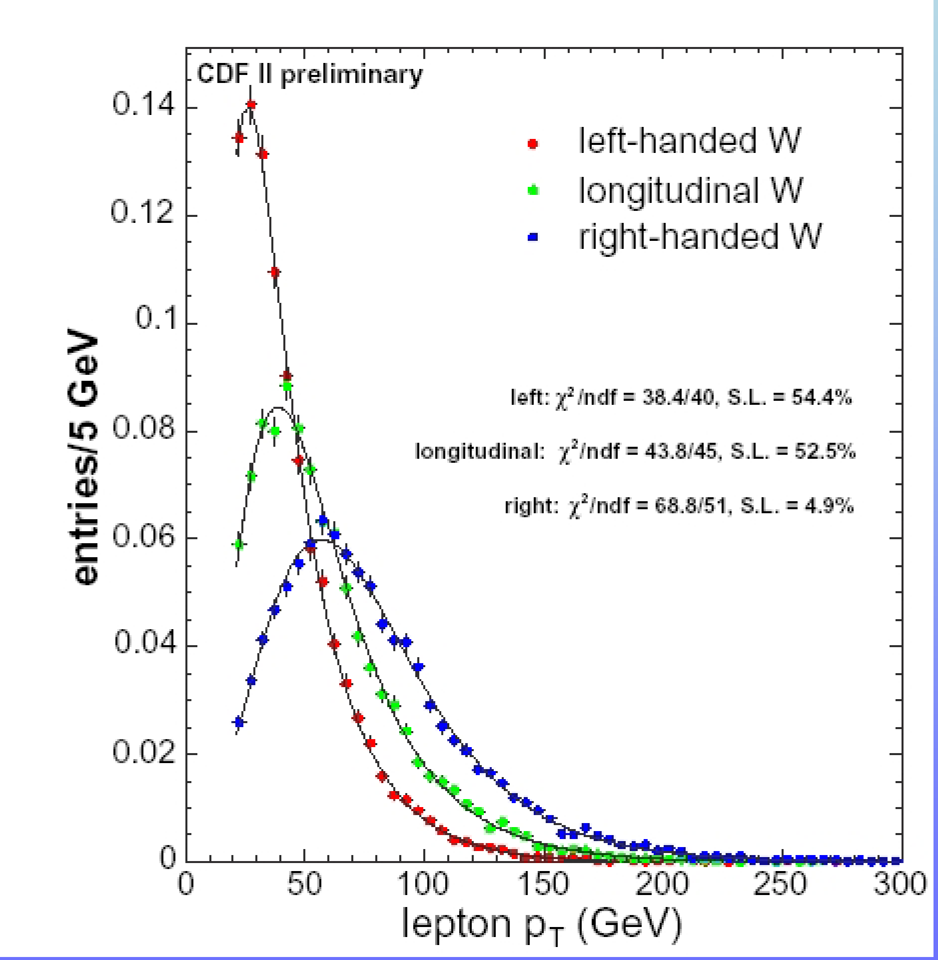
• Extend the ME to include generalized dependence on F_0.

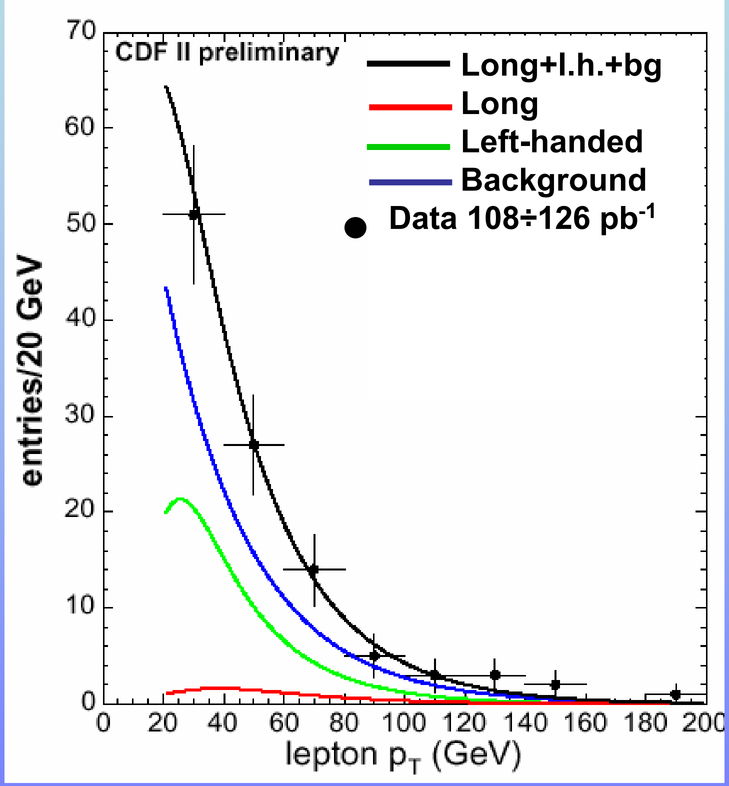
F_0= 0.56 ± 0.31 (stat)±0.04 (syst)



• Application to Run II data is in progress

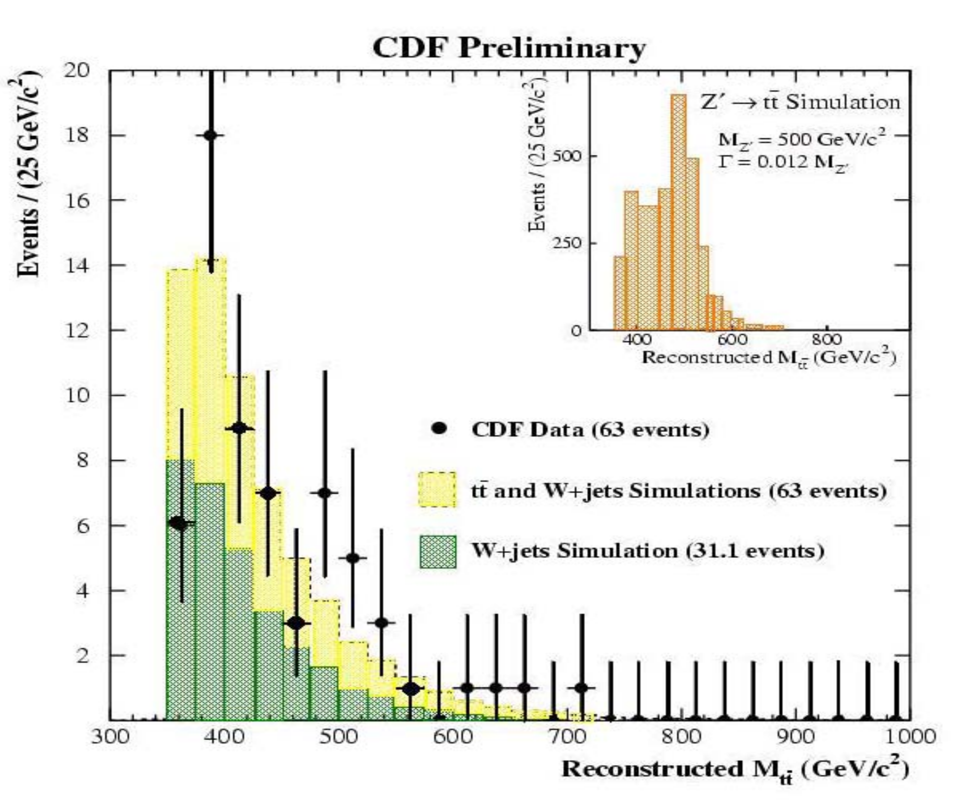
Helicity affects lepton P_T in lab frame

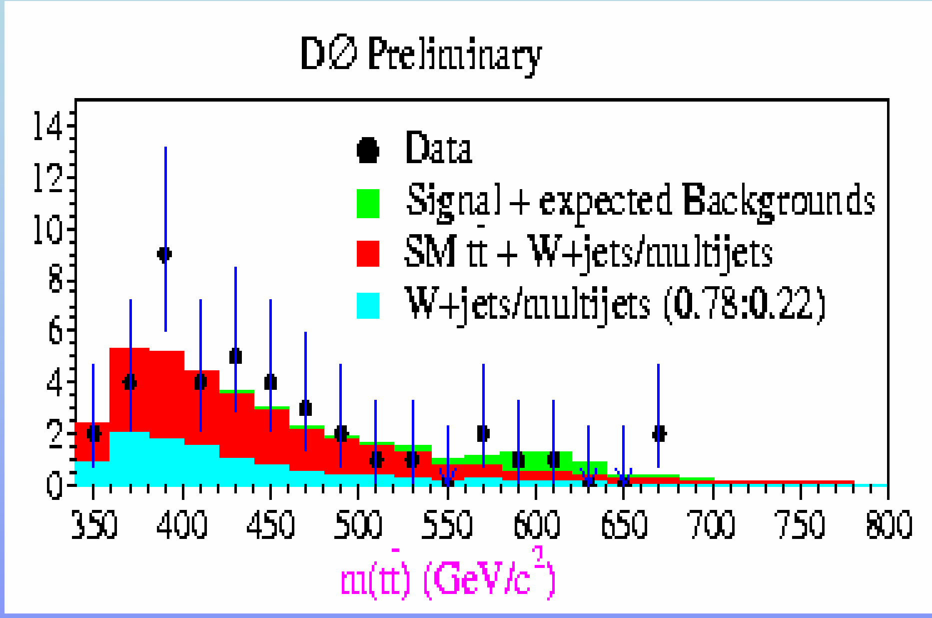




See general agreement with SM, but limited statistics. Analysis in progress.

Test for new physics in $t\bar{t}$ production





Model independent search for a narrow resonance $X \rightarrow t\bar{t}$
exclude a narrow, leptophobic X boson with $m_X < 560$ GeV/c^2 (CDF) and $m_X < 585$ GeV/c^2 (D0)

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Tevatron Luminosity Projections

Integrated Luminosity (fb^{-1})				
	Design Projection		Base Projection	
	per year	Accum-ulated	per year	Accum-ulated
FY03	0.22	0.30	0.20	0.28
FY04	0.38	0.68	0.31	0.59
FY05	0.67	1.36	0.39	0.98
FY06	0.89	2.24	0.50	1.48
FY07	1.53	3.78	0.63	2.11
FY08	2.37	6.15	1.14	3.25
FY09	2.42	8.57	1.16	4.41

With recycler and electron cooling

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Conclusions and Outlook

- The top quark is back!
- First Run II measurements of cross section, mass are available and will improve rapidly.
- Other analyses (W helicity, single top…) are making excellent progress.
- It is the start of a program of precision top physics—and hopefully top surprises—at the Tevatron.
- We still expect at least 50x more data compared to Run I!

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The Road Ahead

- Search for top $\rightarrow H^+$
- Study of τ channels – pure 3rd generation decay mode.
- Single top production, measure V_{tb}
- ttbar resonant production, strong EWSB
- Searches for rare decays
- Is top *the connection* to new physics?

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Top Mass Uncertainties, lepton + jets

CDF Run II Preliminary

Source	Uncertainty (GeV/c^2)
Statistical	+12.7 -9.4
Jet scale	6.2
FSR	2.2
PDFs	2.0
ISR	1.3
Other MC modeling	1.0
Generator	0.6
Backgrounds	0.5
b-tagging	0.1
Total systematic	7.1

Dominated by calorimeter energy scale in simulation; will improve soon

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